VI.5 High Temperature Electrochemistry - Montana State University

Objectives

- Develop thin corrosion resistant coatings on steel interconnect plates that are (1) good electron conductors, (2) thermally stable, (3) good barriers to outward diffusion of Fe and Cr from the interconnect plate, and (4) good barriers to inward oxygen diffusion and growth of oxide scale.
- Characterize the behavior of SOFC interconnect material systems under relevant exposures to develop understanding of essential interfacial chemistry and transport mechanisms.
- Investigate Cr poisoning processes in SOFCs through quantitative measurements of (1) Cr volatility rates from coated/uncoated steel surfaces, and (2) oxygen diffusion and surface exchange rates for electrolyte and cathode materials with surface impurities.
- Investigate the possibility of engineering pore structures and determine their impact on SOFC performance.
- Determine the effects of interfacial strain from lattice mismatch at interfaces of technologically relevant SOFC materials.
- Investigate potential for brazed seals for SOFCs.
- Create an x-ray-compatible electrochemical cell to study the SOFC structural and electronic properties under operational conditions.
- Fabricate and characterize proton conducting ceramics for use in hydrogen separation membranes, intermediate-temperature solid oxide fuel cells, hydrogen pumps, water electrolyzers, and hydrogen sensors.
- Measure and analyze anode gas flow and tortuosity for various anode structures.
- Develop a physically-based dynamic model for a solid oxide fuel cell stack.
- Develop a fuel cell model reference simulator.
- Demonstrate modular power electronics that can be used with transient recognition control (TRC) and develop and demonstrate TRC for fuel cell systems in a field programmable gate array (FPGA) system.
- Develop a DC/DC converter of $40/kW cost and 97% efficiency for the fuel cell powered residential power system.
- Develop a load sharing control method for paralleled DC/AC converters in fuel cell power plants that can ensure the load sharing error is less than 10% in both steady-state and transient conditions.

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Accomplishments

- Demonstrated a rapid, quantitative process using ion beam analysis (Rutherford backscattering spectroscopy, RBS) to measure the evolution in time of Cr volatility for steel surfaces with and without protective coatings.
- Measured oxygen diffusion and surface exchange coefficients for CoMnO coatings deposited on 430 SS, and for surfaces of crystalline YSZ, using nuclear reaction analysis.
- Demonstrated the superior oxidation resistance for short times (<100 hrs) for homogeneous, sputtered CrAlN coatings as compared to multilayered CrN/AlN coatings.
- Developed protective coatings on ferritic steels which demonstrate excellent SOFC interconnect performance, i.e., long-term surface stability, high electronic conductivity and low Cr volatility.
- A vacuum brazing system was designed and constructed and a custom synthesized braze was fabricated at Montana State University (MSU) to improve characteristics of the commercial vehicle in which the successful removal of undesirable silicon components was achieved.
- The Freeze-Tape Casting system is now set up and operational in addition to the freeze drying system for fabrication of graded porous electrode tapes.
- Identified a novel mechanism that may be a serious bottleneck to SOFC performance whereby the strain energy at an SOFC interface is accommodated and distributed over a larger volume (thickness) by modifying the chemical construction of the SOFC

material to improve the lattice mismatch. This new interfacial region has reduced oxygen vacancy mobility.

- Created an x-ray-compatible electrochemical cell and initiated measurements of temperature-dependent structural changes for SOFC materials.
- Optimized fabrication and sintering processes to obtain dense Y-doped $Ba(Ce, Zr)O_3$ proton-conducting ceramics and dense Ni/ceramic cermets with homogenous Ni distribution.
- Achieved good proton conductivities of $Ba_{0.98}(Ce_{0.65}Zr_{0.15}Y_{0.2})O_3$ ceramics at intermediate temperatures (500°-700°C), such as 4.37×10^{-3} $W^{-1}cm^{-1}$ at 500°C, 7.23×10^{-3} $W^{-1}cm^{-1}$ at 600°C, and 1.01×10^{-2} $W^{-1}cm^{-1}$ at 700°C.
- Analyzed anode gas flow results in literature and showed that they indicate tortuosity in the 2 to 4 range.
- Developed a physically-based dynamic model for a 5-kW SOFC stack in the widely used MATLAB/SIMULINK simulation environment.
- Developed and tested circuits for driving fuel cells and/or short stacks with scaled load currents with bandwidths in excess of 100 kHz.
- Demonstrated fixed-point TRC control methods, including transient overlap.
- Implemented TRC at the register transfer level in a Xilinx FPGA.
- Developed a modular power electronics printed circuit board setup using off-the-shelf converters.
- Developed a new DC/DC converter for the fuel cell residential power system. Built both the power circuit and the control circuit of the DC/DC converter. Tested the energy conversion capability of the power circuit and the interleave control functionality of the control circuit.
- Developed and simulated a new load sharing control method for paralleled DC/AC inverters in fuel cell power plants. The simulation results showed that the method could achieve accurate d-q current sharing among all inverters and high-performance zero sequence current control for each of the inverters.

Introduction

MSU-HiTEC is pursuing multiple sub-projects related to the performance, degradation, basic science, and power system engineering relevant to solid oxide fuel cells and electroceramics. These can broadly be categorized into two major groups: 1) materials studies and 2) power electronics and control studies.

Materials Studies

The requirements of low cost and high-temperature corrosion resistance for bipolar interconnect plates in SOFC stacks have directed attention to the use of steel plates with more oxidation resistant compositions. However, volatile Cr species from the chromia-based oxide scales on these steels find their way to the triple-phase boundary, leading to rapid degradation of fuel cell performance. Coatings can serve not only to slow oxidation rates on steel surfaces, but also as diffusion barriers for the Cr-derived species from the steel, slowing the SOFC stack degradation process. We have characterized the oxidation resistance and diffusion behavior of steel plates with coatings of CrAlON and CoMnO, deposited using rf magnetron sputtering and filtered arc deposition techniques. We have also developed a relatively quick, quantitative procedure using Rutherford backscattering spectroscopy (RBS) to measure the time evolution of Cr vaporization rates.

SOFCs are layered devices. The interfacial stress can lead to changes in the electronic, chemical, and structural properties of the materials in the interfacial region that can impact ion transport and other mechanisms that affect fuel cell performance. We have developed a suite of element and site-specific x-ray spectroscopy and x-ray scattering techniques that probe these buried interfacial region properties.

The development of dense and chemically stable proton conducting ceramics with high proton conductivity is critically important for applications of hydrogen separation membranes, proton-conducting-based solid oxide fuel cells, hydrogen pumps, water electrolyzers, and hydrogen sensors. The present work optimized fabrication and sintering processes to obtain dense and stable Y-doped $Ba(Ce, Zr)O_3$ ceramics with high proton conductivities.

Anode-supported solid oxide fuel cells require careful design of the relatively thick anode so fuel gas flow through the anode to the solid electrolyte is not excessively impeded. Experimental work on freeze-tape casting methods to develop graded pore structures is now underway. Detailed analysis of the flow of the fuel gas, and the exhaust gas generated at the anode-electrolyte interface, has been initiated.

Power Electronics and Control Studies

Solid oxide fuel cells are advanced electrochemical energy conversion devices operating at a high temperature, converting the chemical energy of fuel into electric energy at high efficiency. They perform in a fundamentally different fashion than most power systems in wide-scale deployment today. As a result, there is need to develop power electronics, control systems, and system tools that will allow the electrical engineering community to begin development of systems before SOFC stacks are commercially available.

SOFC dynamic modeling is of interest for predicting SOFC performance and controller design for different applications, e.g., for SOFC load transient mitigation and distributed power generation applications.

We are developing a fuel cell reference simulator that will mimic the electrical terminal characteristics of a single cell or short stack but at relevant (kilowatt) power levels. This instrumentation will accelerate development of control systems and power electronics by allowing electrical engineers to work with small, laboratory prototype fuel cells to develop full-scale balance of plant and systems.

Fuel cells are highly efficient but respond slowly to load transients. Additionally, large transients may result in localized heating within the fuel cell and result in degradation of the stack. We are developing novel transient recognition control schemes that will allow intelligent control of fuel cells in multi-source systems. We are also investigating methods of making control systems modular to match the SECA goal of modular fuel cells. Without this, power electronics would require redesign when different numbers of SECA modules are ganged together.

Approaches

Coatings were deposited on 430 and Crofer steel coupons using rf magnetron sputtering at MSU and filtered arc deposition at Arcomac Surface Engineering, Inc. Nitrogen and oxygen gasses were added to the Ar sputtering gas during the growth processes. For sputtered coatings, the Cr/Al composition ratio in the coatings was varied in a combinatorial approach. The coatings were subsequently annealed in air for up to 100 hours at 800°C. The composition of the coated plates, elemental diffusion, and oxidation were characterized using RBS and non-Rutherford backscattering analysis for lighter elements.

In collaboration with coating providers, our group investigates a wide variety of coating techniques, compositions and architectures on different ferritic steels of interest for SOFC interconnects. We subject coated and uncoated materials to SOFC relevant environments and characterize material behavior using an array of analytical techniques and tools, including area specific resistance measurements, indentation testing, surface and cross-section optical and scanning electron microscopy, energy dispersive x-ray spectroscopy, electron backscattered diffraction, x-ray diffraction, Cr volatility measurements using transpiration, and induction-coupled plasma mass spectrometry.

For the Cr volatility measurements, Cr-containing vapors from the steel coupons in a tube furnace at 800ºC were transported with various flow rates of humid air to a Si wafer at ~110ºC near the end of the quartz tube in the furnace, where the vapors adsorbed on the Si surface. The Si wafers were subsequently analyzed for Cr surface concentrations using Rutherford backscattering. Separate experiments with Cr_2O_3 powder as the Cr vapor source established the quantitative reliability of this approach.

The SOFC interfacial stress is controlled by either depositing SOFC films ($La_{0.5}Sr_{0.5}CoO_3$, or LSCO, and $La_{2/3}Ca_{1/3}MnO_3$, or LCMO) grown by pulsed laser deposition on appropriate substrates of known lattice mismatch or by capping thick SOFC structures with wedges of overlayers of known lattice mismatch. This latter method allows for control of the total stress energy with wedge thickness. We have used element and site-specific x-ray spectroscopy and x-ray scattering to study the electronic, chemical, and structural properties of the as-grown systems. Furthermore, films will be similarly studied at operational conditions by using an x-ray compatible electrochemical cell.

By using an optimized Glycine-Nitrate process and investigating the sintering at a series of temperatures and various atmospheres, dense Y-doped $Ba(Ce, Zr)O_3$ ceramics can be obtained. By using the impedance spectroscopy technique, the proton conductivities of grains and grain boundaries were investigated at different temperatures and atmospheres.

The Stefan-Maxwell equation provides a set of differential equations for analyzing flows of each of several gas constituents. Under the condition of fuel gas starvation at the anode-electrolyte interface, these equations can be solved for the anode pore average tortuosity if other experimental parameters are known.

A dynamic model for a 5-kW tubular SOFC stack has been developed based on the SOFC thermodynamic and electrochemical properties and on the mass and energy conservation laws with emphasis on the fuel cell electrical (terminal) characteristics. The SOFC model mainly consists of an electrochemical sub-model, a thermodynamic sub-model, and an electrical circuit model representing the double-layer charging effect. The effect of internal temperature and pressure inside the SOFC on the steady-state V-I (output voltage vs. current) and P-I (output power vs. current) characteristics, and on SOFC response to sudden load changes, were evaluated.

The approach for the fuel cell reference simulator is to develop instrumentation that will mimic the electrical terminal characteristics of a short stack or single cell at power levels. This instrumentation will accelerate development of control systems and power electronics by allowing electrical engineers to work with prototype fuel cells and stacks in full-scale systems.

The approach for transient recognition control is to build a model that recognizes the long-term demand of incoming load transients and controls the fuel cell portion of a multi-source system to meet the long-term demand.

The idea for modular fuel cell power electronics is to investigate a power electronics design paradigm that complements the scalability advantages of fuel cells.

In the DC/DC converter project, we use active switches to control the voltage and therefore the current of the leakage inductance of the transformer and use interleave control to reduce the cost and improve the efficiency of the converter. In the load sharing control project, we drop the d-q voltage with the d-q current in each of the paralleled inverters and control the zero sequence current of each inverter with a newly proposed synchronized pulse-width modulation method.

Results

Significantly improved SOFC interconnect performance has been realized using protective coatings developed by our group. This includes a dramatic improvement in long-term surface stability, increased electronic conductivity, and substantial Cr volatility reduction. Quantified results include the essential absence of physical or chemical changes within the coating for over 1,000 hours at 800°C in air through several thermal cycles; stable area specific resistance values of <10 m$\Omega\cdot cm^2$ for over 1,000 hours in air at 800°C; and a 32-fold reduction in Cr volatility versus uncoated 430 stainless steel. For sputtered CrAlON coatings, we observed that Al-rich coatings are more susceptible to oxidation than Cr-rich coatings and that a Cr/Al ratio of 0.9 provides good oxidation resistance.

We contrasted the early time evolution of Cr volatility for 430 SS and for CroferAPU22, the latter with and without a CoMnO spinel coating deposited using a combination of filtered arc and rf magnetron sputtering processes. The coated materials showed a significant reduction in Cr volatility indicating that such coatings may be a viable strategy for prevention of Cr poisoning of SOFCs (Figure 1).

By using polarization dependent x-ray absorption spectroscopy (XAS), we have examined the chemical state of different elements of $La_{2/3}Ca_{1/3}MnO_3$ (LCMO) and $La_{0.5}Sr_{0.5}CoO_3$ (LSCO) at room temperature as a function of the stress within the films created by the substrate or overlayer lattice mismatch on which the film is grown. We have found that as the stress is changed from compressive to tensile stress, the chemical state of the Co in the interfacial region changes dramatically, although the structure of the film remains essentially unchanged. The SOFC films were grown in a series of thicknesses (up to 2500 Å) on various single crystal substrates [strontium titanate - $SrTiO_3$ (STO),

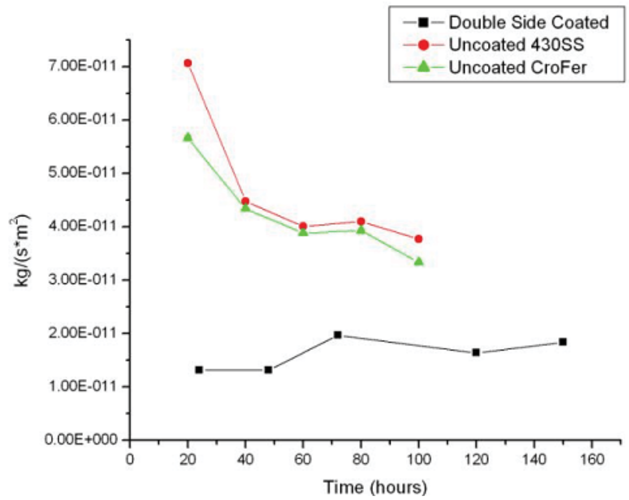

FIGURE 1. Cr Vaporization Rates of Coated and Uncoated Steels as a Function of Time at 800°C in Humid Air

neodymium gallium oxide - $NdGaO_3$ (NGO), strontium ruthenate - $SrRuO_3$ (SRO), and lanthanum aluminum oxide - $LaAlO_3$ (LAO)]. Representative of the results are the XAS spectral shifts of LSCO as the thickness of an LAO overlayer is increased (Figure 2). The stress response is for the SOFC to create a compositional gradient to distribute the stress energy over a larger volume (film thickness). The compositional gradient region represents a region where the transition metal ion valence is changing and the oxygen vacancy diffusion is far from optimum. In some extreme cases, the oxygen vacancy diffusion may become negligible, compromising SOFC performance.

We optimized the fabrication processes of Y-doped $Ba(Ce, Zr)O_3$ ceramics and Ni/ceramic cermets. Proton conductivities of the grains and grain boundaries in the ceramic samples were investigated by impedance spectroscopy in different atmospheres (3% H_2/97% He with saturated water vapor, air, and air with saturated water vapor). Figure 3 shows the conductivity Arrhenius plot of $Ba_{0.98}(Ce_{0.65}Zr_{0.15}Y_{0.2})O_3$ ceramics at temperatures 100º-800ºC. The activation energy changes near 600ºC, which may indicate a conduction mechanism change. Coors and Readey [1] first observed a marked change of proton conductivity activation energy in $Ba(Ce_{0.9}Y_{0.1})O_3$ ceramics at ~250ºC. Accordingly, our substitution of Ce with Zr significantly increased this transition temperature. The activation energies in our samples (0.29 and 0.58 eV) are very close to those (0.26 and 0.56 eV) of Coors and Readey. Good proton conductivities of $Ba_{0.98}(Ce_{0.65}Zr_{0.15}Y_{0.2})O_3$ ceramics at intermediate temperatures (500º-700ºC) were obtained, such as $1.01\times10^{-2}\ \Omega^{-1}cm^{-1}$ at 700ºC.

Literature results for anode saturation current density for various combinations of fuel and diluent input gases were analyzed to calculate the average anode

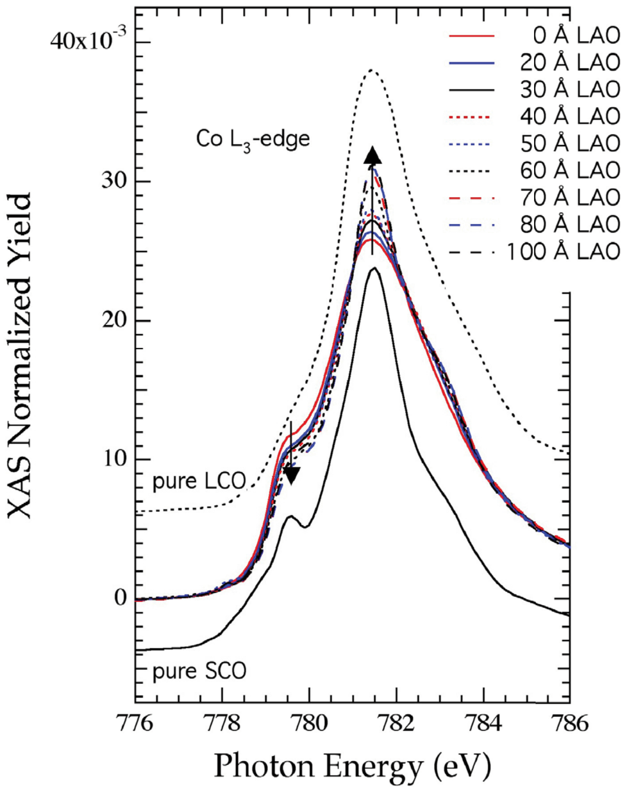

FIGURE 2. Co $L_{2,3}$ edge XAS spectra for LSCO thin films capped with LAO shown as a function of overlayer thickness (increased induced stress in the LSCO films). Also shown are spectra for pure SCO and pure LCO.

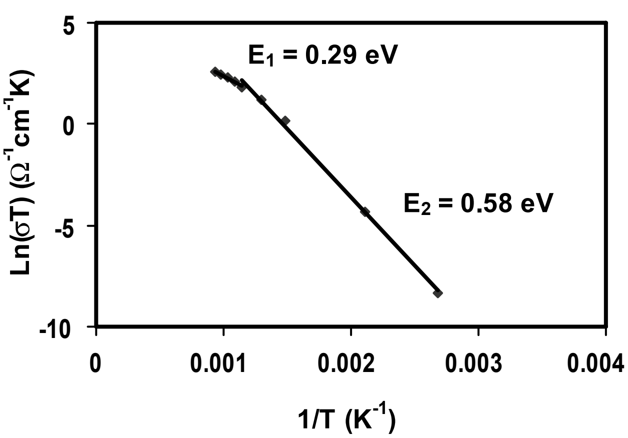

FIGURE 3. Arrhenius plot of proton conductivities (grain plus grain-boundary conductivities) of $Ba_{0.98}(Ce_{0.65}Zr_{0.15}Y_{0.2})O_{3-\delta}$ ceramics, with activation energies $E_1 = 0.29$ eV at 600-800°C and $E_2 = 0.58$ eV at 100-600°C.

pore tortuosity. Physically reasonable tortuosity values of 2 to 4 were calculated, much lower than some values in the literature. Detailed understanding of anode gas flow as influenced by tortuosity and other factors is required to optimize anode design in anode-supported SOFCs.

The voltage and power output of the SOFC stack model depend on conditions including fuel composition, fuel flow, oxidant flow, anode and cathode pressures, cell temperature, load current and the electrical and thermal properties of the cell materials. There is a time constant associated with the SOFC stack output voltage due to the double-layer charging effect (in the millisecond range), one due to the internal pressure (in the second range), and one due to temperature (in the minute range). Figure 4 (top) shows the V-I characteristics of the SOFC stack model (developed at MSU) at different temperatures, and Figure 4 (bottom) shows the same characteristics from the SECA model for a single cell provided to us.

Challenges for the fuel cell reference simulator addressed in this last year's work included developing high-performance analog electronics to drive current on the fuel cell side of the system, and high power voltage output amplifiers to drive the load side of the system. We assembled the voltage amplifier by paralleling three off-the-shelf amplifiers. The fuel cell side current source required custom design, and a printed circuit board was fabricated and modified to achieve acceptable performance. A working prototype design has been finalized and tested in the loop using a dry cell as a substitute for the fuel cell. Preliminary results show that this system mimics the dynamic response of the small power source (such as a button-cell SOFC) with high fidelity, but amplifies power levels to the several kilowatt range.

For the modular power electronics demonstration, we were able to use six Synqor power electronics modulars to create a multisource converter that could be used in conjunction with TRC. Unfortunately, the proposed scheme for controlling current on the fuel cell of this converter did not work due to the design of Synqor's current sharing. We were able to develop an alternative strategy but have not yet tested it.

An implementation of TRC in a Xlinix FPGA was accomplished. Although this implementation lacks some of the refinements needed for production use, it does demonstrate the feasibility of using transient recognition control for real-time mitigation of fuel cell/transient interactions.

The power circuit of the DC/DC converter can successfully boost a 25 V DC voltage to a 350 V one. The control circuit of the DC/DC converter can successfully produce proper control signals to implement the interleave control.

Simulation results showed that the proposed load sharing control method could achieve even load sharing among all inverters and control the zero sequence current of each inverter.

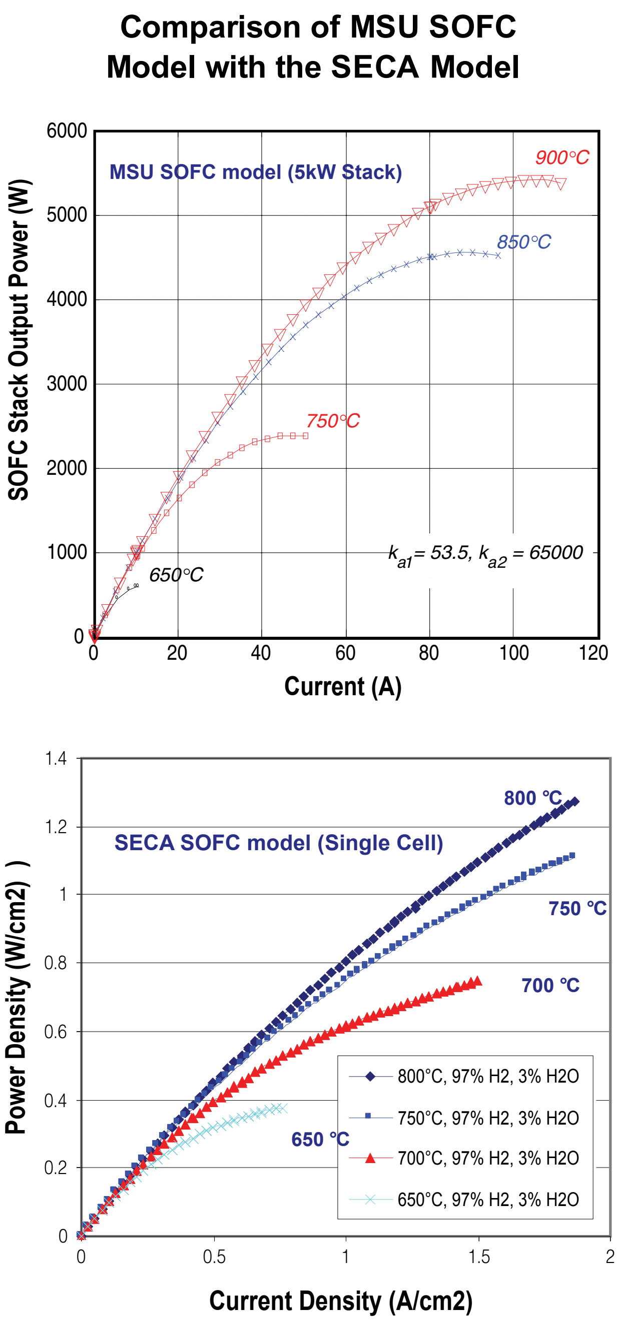

FIGURE 4. V-I Characteristics of the SOFC Model at Different Temperatures

Conclusions and Future Directions

We have explored a wide variety of coating techniques, compositions and architectures to enable the use of inexpensive ferritic steels as interconnects in SOFCs operating at 800°C. A combination of a filtered arc deposited adhesion-promoting, electronically conductive diffusion barrier CrAlYO bottom segment coating, followed by a filtered arc-assisted electron beam evaporated Cr-retentive and cathode compatible CoMnO top segment coating demonstrates excellent SOFC interconnect operating characteristics on commercially available 430 stainless steel. Future work will focus on optimizing coating composition and architecture and evaluating material systems under more prototypical SOFC exposures. Measurements of corrosion resistance with structured coatings, e.g., substrate/bondcoat/topcoat, to achieve good coating adhesion are planned. Measurements of oxygen transport in coatings and the effects of Cr surface contamination on oxygen exchange at cathode/electrolyte surfaces are underway. Growth of thin, dense YSZ films on porous YSZ anode material is currently under investigation for fabrication of thin SOFCs with reduced operating temperatures.

We will conduct similar X-ray experiments for other candidate SOFC materials such as $La_{0.5}Sr_{0.5}FeO_3$ and under operating fuel cell conditions.

Simulation results from the dynamic SOFC model developed compare well with the data provided to us from the SECA Excel model and in the SOFC research literature. The model is implemented in MATLAB/SIMULINK, a common modeling package used by the electrical engineering community and should help that community develop familiarity with SOFCs.

The fuel cell reference simulator development is making good progress. It is an important tool for allowing development of power electronics and control for SOFCs in parallel with the SOFC development. We need to complete whole system testing of the simulator.

We need to revise our proposed method for testing the interleaved modular power electronics and integrate this with TRC.

Special Recognitions & Awards/Patents Issued

1. TRC patent is pending.
2. S.R. Shaw received a National Science Foundation Career award.

FY 2006 Publications/Presentations

1. A. Kayani, R.J. Smith, S. Teintze, M. Kopczyk, P.E. Gannon, M.C. Deibert, V.I. Gorokhovsky, V. Shutthanandan, "Oxidation Studies of CrAlON Nanolayered Coatings on Steel Plates," *Surface Coatings and Technology*, accepted 2006.
2. A. Kayani, T.L. Buchanan, M. Kopczyk, C. Collins, J. Lucas, K. Lund, R. Hutchison, P.E. Gannon, M.C. Deibert and R.J. Smith, "Oxidation Resistance at 800°C for Magnetron-Sputtered CrAlN Coatings on 430 Steel," presented at International Conference on Metallurgical Coatings and Thin Films, San Diego, CA, May, 2006; submitted for publication to *Surface and Coatings Technology*, February 2006.

3. C. Collins, J. Lucas, T.L. Buchanan, M. Kopczyk, A. Kayani, P.E. Gannon, M.C. Deibert, R.J. Smith, D.S. Choi, V.I. Gorokhovsky, "Chromium Volatility of Coated and Uncoated Steel Interconnects for SOFCs," presented at International Conference on Metallurgical Coatings and Thin Films, San Diego, CA, May, 2006; submitted for publication to *Surface and Coatings Technology*, February 2006.

4. C. Wang and M.H. Nehrir, "A Dynamic SOFC Model for Distributed Power Generation Applications," Proceedings, 2005 Fuel Cell Seminar, Palm Springs, CA, November 2005.

5. C. Wang and M.H. Nehrir, "Distributed Generation Applications of Fuel Cells," Proceedings, 2006 Power Systems Conference, Clemson, SC, March 2006.

6. C. Wang and M.H. Nehrir, "Load Transient Mitigation for Solid Oxide Fuel Cells," Proceedings, 2006 ASME Fuel Cell Science, Engineering and Technology Conference, Irvine, CA, June 21, 2006.

7. C. Wang, M.H. Nehrir, and H. Gao, "Control of PEM Fuel-Cell Distributed Generation Systems," paper to be presented at the 2006 IEEE Power Engineering General Meeting, Montreal, Canada, June 2006; published in *IEEE Transactions on Energy Conversion*, Vol. 21, No. 2, June 2006.

8. E. Negusse and Y.U. Idzerda, "Extraction of Roughness Parameters from Specular X-Ray Resonant Scattering," *J. Appl. Phys.*, 2005. 97: p. 10C901.

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10. M.H. Nehrir, "Modeling and Control of SOFC for Distributed Generation Applications," presentation of SOFC Dynamic model development at NETL, Morgantown, WV, March 2006.

11. M.H. Nehrir, C. Wang, and S.R. Shaw, "Fuel Cells: Promising Devices for Distributed Generation, Understanding their Modeling and Need for Control," *IEEE Power and Energy Magazine*, Vol. 4, No. 1, January/February 2006.

12. P.E. Gannon, V.I. Gorokhovsky, M.C. Deibert, R.J. Smith, A. Kayani, P.T. White, Z. Gary Yang, J.W. Stevenson, S. Visco, C. Jacobson, H. Kurokawa, S.W. Sofie, "Enabling Inexpensive Metallic Alloys as SOFC Interconnects: an Investigation into Hybrid Coating Technologies to Deposit Nanocomposite Functional Coatings on Ferritic Stainless Steels," presented at 135th annual TMS meeting, San Antonio, TX, March 2006, accepted for publication in *International Journal of Hydrogen Energy*.

13. P.E. Gannon, V.I. Gorokhovsky, M.C. Deibert, R.J. Smith, A. Kayani, S. Sofie, Z. Gary Yang, J.W. Stevenson, S. Visco, C. Jacobson, H. Kurokawa, "Investigating Hybrid Filtered Arc Plasma Source Ion Deposition Technologies to Deposit Nanostructured Functional Coatings on Ferritic Stainless Steels. Part II: Simulated Solid Oxide Fuel Cell Interconnect Performance," presented at 2006 International Conference on Metallurgical Coatings and Thin Films; manuscript in preparation.

14. R. Sharma and H. Gao, "A New DC-DC Converter for Fuel Cell Powered Distributed Residential Power Generation Systems," presented in IEEE Applied Power Electronics Conference and Exposition, Dallas, TX, March 2006.

15. R. Sharma and H. Gao, "Low Cost High Efficiency DC-DC Converter for Fuel Cell Powered Auxiliary Power Unit of a Heavy Vehicle," accepted for publication in *IEEE Transactions on Power Electronic*s, November 2005.

16. S.R. Shaw, "Transient Recognition Control for Fuel Cell Systems," SECA CTP Peer Review Meeting (Invited), October 25, 2005.

17. T. Zhu, "Extended Cluster Weighted Modeling Methods for Transient Recognition Control," Ph.D. Thesis, June 2006.

18. V.I. Gorokhovsky, P.E. Gannon, M.C. Deibert, R.J. Smith, A. Kayani, M. Kopczyk, D. VanVorous, Z. Gary Yang, J.W. Stevenson, S. Visco, C. Jacobson, H. Kurokawa, S.W. Sofie, "High Temperature Oxidation, Cr Volatility and Surface Electrical Conductivity of Ferritic Steel with Filtered Arc and Hybrid Filtered Arc-Assisted EBPVD Coatings," accepted for publication in *Journal of the Electrochemical Society*.

19. V.I. Gorokhovsky, P.E. Gannon, M.C. Deibert, R.J. Smith, A. Kayani, S. Sofie, Z. Gary Yang, J.W. Stevenson, "Investigating Hybrid Filtered Arc Plasma Source Ion Deposition Technologies to Deposit Nanostructured Functional Coatings on Ferritic Stainless Steels. Part I: Deposition Process Parameters and Basic Coating Characteristics," presented at 2006 International Conference on Metallurgical Coatings and Thin Films; manuscript in preparation.

20. C. Wang, M.H. Nehrir, "A Physically-Based Dynamic Model for Solid Oxide Fuel Cells," paper conditionally accepted for publication in the *IEEE Transactions on Energy Conversion* (April 2006).

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